Experimental Evaluation of the Out-of-Plane Behavior of Infilled Masonry Walls Isolated from RC Frames and Retrofitted with Glass Fiber and Steel Angles

Milad faraji[1], Jalil shafaei[2]*, Farnoush baseligha[3], Mohammadjavad zarei[4]

Department of Civil Engineering, Shahrood University of Technology, Shahrood, Iran.

* jshafaei@shahroodut.ac.ir

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Abstract

Masonry infills are among the most common nonstructural components in reinforced concrete (RC) buildings. However, past earthquakes, including the 2017 Kermanshah earthquake, have demonstrated their vulnerability to out-of-plane (OOP) loading, which can lead to severe damage and adverse interactions with adjacent structural members. This study experimentally investigates the OOP behavior of three 1:2-scale, single-bay RC frames with clay masonry infills subjected to cyclic, displacement-controlled loading. The specimens consisted of a fully connected, unretrofitted infill (OOP-NI-FI), an unretrofitted infill isolated from the columns by 20 mm gaps (OOP-I-FI), and an isolated infill retrofitted with alkali-resistant (AR) glass fiber mesh and intermittent steel angles (OOP-I-RFI). Isolation alone reduced the peak load by approximately 6.1%, from 16.67 to 15.65 kN, and decreased the initial stiffness. Nevertheless, the isolated specimen exhibited a more gradual post-cracking response while retaining the potential for two-way arching action. The combined isolation and retrofit system increased the peak load to 25.30 kN, representing a 51.8% improvement over the benchmark specimen. It also achieved an initial stiffness of 1.00 kN/mm, a secondary stiffness of 1.49 kN/mm, and an energy dissipation capacity of 724.66 J, while sustaining an ultimate displacement of approximately 70 mm. These findings indicate that combining infill isolation with AR glass fiber mesh and intermittent steel angles can substantially improve the OOP strength, deformation capacity, and energy dissipation of masonry infills. Further testing is required to establish the general applicability of the proposed system.

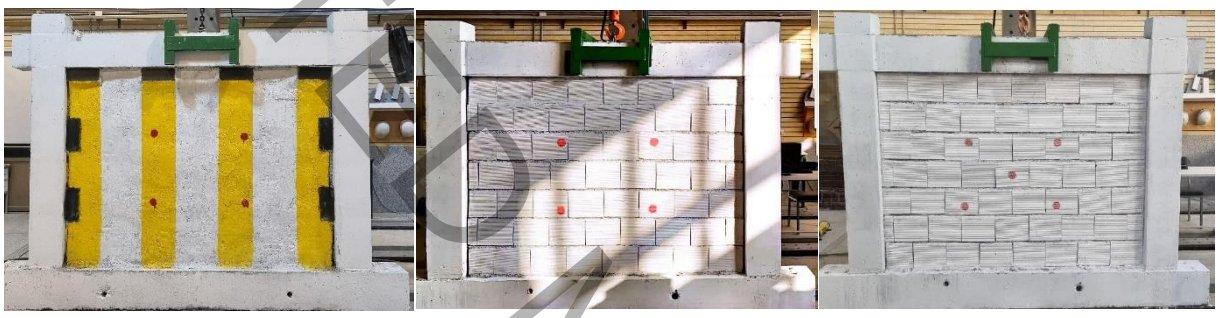
1. Introduction

Masonry infills are common in reinforced concrete (RC) buildings, but inadequate anchorage can cause severe out-of-plane (OOP) damage and collapse during earthquakes. This study experimentally investigates the effects of combining discontinuous steel angles and alkali-resistant glass (AR-Glass) fiber mesh on the OOP response of clay masonry infill walls. Dawe and Seah (1989) demonstrated the importance of frame stiffness for arching action and post-cracking ductility [1]. Koutas et al. (2019) showed that effective anchorage of textile-reinforced mortar improves load-bearing capacity and prevents premature shear failure [2]. Pradhan et al. (2021) confirmed the importance of boundary confinement for OOP resistance [3]. Ostad et al. (2026) demonstrated that AR-Glass fiber strips enhance load capacity, energy dissipation, and wall integrity [4]. Similarly, Zarei et al. (2026) showed that combining localized restraints with AR-Glass fibers improves OOP seismic performance and ductility [5]. Despite these advances, the combined effects of infill isolation, discontinuous steel angles, and AR-Glass fiber mesh have rarely been investigated experimentally. This study examines three 1:2-scale RC frame specimens under cyclic OOP loading: a fully connected, unretrofitted infill; an isolated,

unretrofitted infill; and an isolated infill retrofitted with AR-Glass mesh and discontinuous steel angles. Their load-bearing capacity, stiffness degradation, deformation ductility, and failure mechanisms are compared to evaluate the effectiveness of the proposed hybrid retrofit system.

Methodology

The experimental program involved three 1:2-scale, single-bay RC frames (2000 × 1500 mm) tested under cyclic out-of-plane loading. The specimens comprised a connected, unretrofitted infill (OOP-NI-FI), an isolated infill with 20 mm gaps along both columns (OOP-I-FI), and an isolated infill retrofitted with alkali-resistant (AR) glass fibers and intermittent steel angles (OOP-I-RFI). Materials were characterized using standard tests, including ASTM C67 for clay blocks and ASTM A370 for reinforcing bars. The retrofit system incorporated fiber mesh and steel anchors connecting the wall edges to the beam and foundation. Displacement-controlled loading was applied using a hydraulic jack, while LVDTs recorded wall displacements. Peak load, initial and secondary stiffness, energy dissipation, and crack patterns were evaluated to compare the specimens' out-of-plane performance. Fig. 1



RFI-I-OOP (c FI-I-OOP (b FI-NI-OOP (a

Fig. 1. General views of the fabricated specimens after curing, prior to out-of-plane testing: (a) FI-NI-.OOP; (b) FI-I-OOP; and (c) RFI-I-OOP

Results and Discussion

The connected specimen (OOP-NI-FI) reached a peak load of 16.67 kN at 21.01 mm, with initial and secondary stiffnesses of 0.961 and 0.792 kN/mm, respectively, and energy dissipation of 244 J. Local crushing and arching governed its failure, preventing sudden collapse. The isolated specimen (OOP-I-FI) achieved a peak load of 15.65 kN, approximately 6.1% below the benchmark. Its initial stiffness decreased to 0.571 kN/mm, while secondary stiffness increased to 0.832 kN/mm. Its staged failure indicated a more gradual post-cracking response. The retrofitted specimen (OOP-I-RFI) exhibited the best performance, reaching 25.30 kN peak load, 1.00 kN/mm initial stiffness, 1.49 kN/mm secondary stiffness, and 724.66 J energy dissipation. Its ultimate displacement reached approximately 70 mm, demonstrating substantially improved ductility and post-cracking capacity. Overall, the 20 mm isolation gap reduced initial stiffness and slightly decreased strength but delayed rather than prevented arching. The retrofit effectively compensated for these effects, significantly enhancing strength, ductility, and energy dissipation. Fig. 2.

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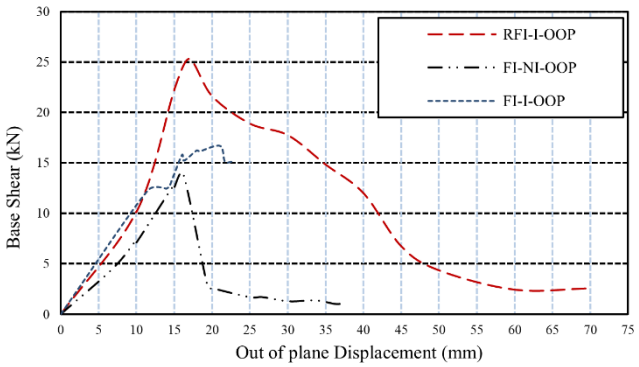

Fig. 2. Comparison of the envelope curves for the laboratory specimens under out-of-plane loading.

Conclusion

The out-of-plane response of masonry infills depends on material strength, boundary conditions, force transfer, and retrofit configuration. The 20 mm isolation gap reduced peak load by 6.1% and initial stiffness but mitigated destructive frame–infill interaction. Combining AR-glass fibers with intermittent steel angles compensated for this reduction, increasing peak load by 51.8%, secondary stiffness from 0.792 to 1.49 kN/mm, and energy dissipation from 244 to 724.66 J, while extending ultimate displacement to approximately 70 mm. The retrofit also improved edge anchorage, preserved wall integrity, and prevented sudden collapse while maintaining the arching mechanism. These findings highlight the effectiveness of the combined isolation and retrofit system for improving masonry infill performance under out-of-plane loading. However, the limited number of specimens, laboratory constraints, scaled masonry units, and qualitative assessment of arching mechanisms restrict generalization. Future research should include replicate tests, investigate in-plane and combined in-plane/out-of-plane behavior, and develop numerical models.

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